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Probing transverse quark polarization via azimuthal asymmetries in leptonproduction

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Abstract

We consider the leading order result for polarized leptonproduction, putting emphasis on transverse momentum dependent effects appearing in azimuthal asymmetries.

Measurements of weighted cross sections enable extraction of the distribution of transversely polarized quarks. We focus on the distribution in a longitudinally polarized hadron and estimate the expected asymmetries in leptonproduction. © 1997 Elsevier Science B.V.

1. Introduction

For the study of azimuthal distributions of hadrons produced in deep inelastic lepton-hadron scattering, the transverse momenta of quarks with respect to the hadron in the quark distribution functions (DF's) and in the quark fragmentation functions (FF's) play an important role, even in leading order in $1/Q$ where $Q^2 = -q^2$ is the momentum transfer squared. Omitting details that can be found in [1,2] and restricting ourselves to leading order in $1/Q$, the six DF's needed to describe the quark density matrix in a nucleon depend on x and p_T which parametrize (the relevant part of) the quark momentum p , in a nucleon with momentum P , $p = xP + p_T$. The subscript T refers to transverse with respect to the momenta of target hadron (P) and produced hadron (P_h). For a polarized nucleon the spin vector is written as $S = \lambda P/M + S_T$, satisfying $\lambda^2 - S_T^2 = 1$. Then, the probability $\mathcal{P}_N^q(x, p_T^2)$, the longitudinal spin distribution $\lambda^{(in)q}(x, p_T)$, and the transverse spin distributions $s_T^{(in)q}(x, p_T)$, of the quark in a polarized nucleon are given by

$$\mathcal{P}_N^q(x, p_T) = f_1^q(x, p_T^2), \quad (1)$$

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$$\mathcal{P}_N^q(x, p_T) \lambda^{(\text{in})q}(x, p_T) = \lambda g_{1L}^q(x, p_T^2) - \frac{p_T \cdot S_T}{M} g_{1T}^q(x, p_T^2), \quad (2)$$

$$\mathcal{P}_N^q(x, p_T) s_t^{(\text{in})q}(x, p_T) = S_T h_{1T}^q(x, p_T^2) + \frac{p_T}{M} \left[\lambda h_{1L}^{\perp q}(x, p_T^2) - \frac{p_T \cdot S_T}{M} h_{1T}^{\perp q}(x, p_T^2) \right]. \quad (3)$$

In inclusive processes one only encounters p_T -integrated results. Integrating the lefthandside over p_T one finds on the righthandside x -dependent distribution functions,

$$\int d^2 p_T \mathcal{P}_N^q(x, p_T) = f_1^q(x), \quad (4)$$

$$\int d^2 p_T \mathcal{P}_N^q(x, p_T) \lambda^{(\text{in})q}(x, p_T) = \lambda g_1^q(x), \quad (5)$$

$$\int d^2 p_T \mathcal{P}_N^q(x, p_T) s_t^{(\text{in})q}(x, p_T) = S_T \left(h_{1T}^q(x) + h_{1T}^{\perp(1)q}(x) \right) \equiv S_T h_1^q(x), \quad (6)$$

where we have straightforwardly p_T -integrated functions and $(-p_T^2/2M^2)$ -weighted functions indicated with superscript (1).

$$f(x) = \int d^2 p_T f(x, p_T^2), \quad (7)$$

$$f^{(1)}(x) = \int d^2 p_T \left(\frac{-p_T^2}{2M^2} \right) f(x, p_T^2). \quad (8)$$

The function $f_1^q(x)$ is the familiar quark distribution function, also often denoted as $q(x)$, $g_1^q(x)$ and $h_1^q(x)$ are the longitudinal and transverse spin quark distribution functions, also often denoted as $\Delta q(x)$ and $\Delta_T q(x)$. Two other $(-p_T^2/M^2)$ -weighted functions appear in the single (p_T/M) -weighted results for polarized quarks,

$$\int d^2 p_T \frac{p_T}{M} \mathcal{P}_N^q(x, p_T) \lambda^{(\text{in})q}(x, p_T) = S_T g_{1T}^{(1)q}(x), \quad (9)$$

$$\int d^2 p_T \mathcal{P}_N^q(x, p_T) \frac{p_T \cdot S_T s_t^{(\text{in})q}(x, p_T)}{M} = \lambda h_{1L}^{\perp(1)q}(x). \quad (10)$$

In the analysis of the current jet in hadroproduction one encounters at leading order fragmentation functions depending on z and $P_{h\perp}$ – the hadron transverse momenta with respect to the quark momenta, which describe the decay of a quark with momentum k into a hadron with momentum $P_h = z k + P_{h\perp}$. This is equivalent to a quark with momentum $k = P_h/z + k_T$ producing a hadron with momentum P_h provided its transverse momentum is given by $k_T = -P_{h\perp}/z$. For the case that no polarization in the final state is measured one has quark fragmentation functions, defined via the quark decay function

$$\mathcal{D}_h^q(z, k_T) = D_1^q(z, P_{h\perp}^2 = z^2 k_T^2) + \frac{\epsilon_{ij}^{ij} k_{Ti} s_{Tj}^{(\text{out})q}}{M_h} H_1^{\perp q}(z, z^2 k_T^2), \quad (11)$$

where $s_T^{(\text{out})q}$ is the transverse polarization of the fragmenting quark. The second fragmentation function allowing the possibility of a correlation between the produced hadron transverse momentum and the transverse polarization of fragmenting quark is nonzero because of non-applicability of time reversal invariance in a decay process [3–5,2]. This specific function was first discussed by Collins [6]. Upon k_T -integration of the lefthandside one finds the following nonvanishing combinations

$$\int d^2 P_{h\perp} \mathcal{D}_h^q(z, k_T) = \int d^2 P_{h\perp} D_1^q(z, P_{h\perp}^2) = z^2 \int d^2 k_T D_1^q(z, z^2 k_T^2) \equiv D_1^q(z), \quad (12)$$

$$\int d^2 P_{h\perp} \mathcal{D}_h^q(x, k_\tau) \frac{\epsilon_T^{ij} k_{\tau i} s_{Tj}^{(\text{out})q}}{M_h} = z^2 \int d^2 k_\tau \left(\frac{-k_\tau^2}{2M_h^2} \right) H_1^{\perp q}(z, z^2 k_\tau^2) \equiv H_1^{\perp(1)q}(z). \quad (13)$$

The function $D_1^q(z)$ is the familiar fragmentation function, normalized through the momentum sum rule $\sum_h \int dz z D_1^{q \rightarrow h}(z) = 1$.

One of the reasons to consider transverse momentum dependent distribution and fragmentation function is their appearance in measurements of azimuthal asymmetries in Drell-Yan scattering, 1-particle inclusive leptonproduction, or in jet analysis in e^+e^- annihilation. On the theoretical side there is the relation of transverse momentum dependent functions and higher twist functions as discussed in Ref. [2]. We mention particularly the relations with the twist-three quark distributions g_T^q and h_L^q ,

$$g_T^q(x) = g_1^q(x) + \frac{d}{dx} g_{1T}^{(1)q}, \quad (14)$$

$$h_L^q(x) = h_1^q(x) - \frac{d}{dx} h_{1L}^{\perp(1)q}. \quad (15)$$

The first distribution appears in the structure function g_2^q measured in inclusive deep inelastic scattering, while the latter appear for instance in Drell-Yan asymmetries [7]. The first relation was discussed earlier in a slightly different framework in Ref. [8].

2. The polarized semi-inclusive cross section

The cross section for 1-particle inclusive deep inelastic scattering is given by

$$\frac{d\sigma^{(\ell+N \rightarrow \ell' + h + N)}}{dx dy dz d\phi^\ell d^2 P_{h\perp}} = \frac{\alpha^2}{2Q^4} \frac{y}{2z} L_{\mu\nu} 2M\mathcal{W}^{\mu\nu}, \quad (16)$$

where the scaling variables are defined as $x = Q^2/2P \cdot q$, $y = P \cdot q/P \cdot l$ (l is a momentum of incoming lepton) and $z = P \cdot P_h/P \cdot q$. We have not bothered to introduce different notations for the momentum fractions x and z used in the previous section and the scaling variables as they will be identified in the leading order calculation. The transverse space (e.g. $P_{h\perp}$) is defined with respect to the momenta P and q . The azimuthal angles are angles in the transverse space giving the orientation of the lepton plane (ϕ^ℓ) and the orientation of the hadron plane ($\phi_h^\ell = \phi_h - \phi^\ell$) or spin vector ($\phi_s^\ell = \phi_s - \phi^\ell$) with respect to the lepton plane. The angles all are defined around the z -axis defined by the momenta P and q . The quantity $L_{\mu\nu}$ is the well-known lepton tensor, while the hadronic tensor is given by

$$2M\mathcal{W}_{\mu\nu}(q; PS; P_h) = \int \frac{d^3 P_X}{(2\pi)^3 2P_X^0} \delta^4(q + P - P_X - P_h) \langle PS | J_\mu(0) | P_X; P_h \rangle \langle P_X; P_h | J_\nu(0) | PS \rangle. \quad (17)$$

At leading order the calculation only involves the DF's and FF's discussed in the previous section, and each quark (and antiquark) contributes

$$2M\mathcal{W}_{\mu\nu} = 2z \sum_q e_q^2 \int d^2 k_\tau d^2 p_\tau \delta^2 \left(p_\tau - k_\tau - \frac{P_{h\perp}}{z} \right) f_1^q(x, p_\tau^2) D_1^q(z, z^2 k_\tau^2) \\ \times \left[-g_T^{\mu\nu} + i\lambda^{(\text{in})} \epsilon_T^{\mu\nu} + s_r^{(\text{in})} \{ \mu s_r^{(\text{out})\nu} \} - s_r^{(\text{in})} \cdot s_r^{(\text{out})} g_r^{\mu\nu} \right]. \quad (18)$$

Performing the contraction this leads to the cross section as shown first in [9] with the following terms

$$\frac{d\sigma^{\ell+N \rightarrow \ell'+h+X}}{dx dy d\phi^\ell dz d^2 P_{h\perp}} = \frac{\alpha^2}{Q^2 y} \sum_q e_q^2 \sigma_q, \quad (19)$$

where

$$\begin{aligned} \sigma_q = & \int d^2 p_T d^2 k_T \delta^2 \left(p_r - k_r - \frac{P_{h\perp}}{z} \right) \\ & \times \left\{ [1 + (1-y)^2] f_1^q(x, p_r^2) D_1^q(z, z^2 k_T^2) + \lambda_e \lambda y (2-y) g_1^q(x, p_r^2) D_1^q(z, z^2 k_T^2) \right. \\ & - \lambda_e y (2-y) \frac{(p_r \cdot S_r)}{M} g_{1T}^q(x, p_r^2) D_1^q(z, z^2 k_T^2) - 2(1-y) \frac{k_r^1 S_r^2 + k_r^2 S_r^1}{M_h} h_{1T}^q(x, p_r^2) H_1^{\perp q}(z, z^2 k_T^2) \\ & - \lambda 2(1-y) \frac{k_r^1 p_r^2 + k_r^2 p_r^1}{MM_h} h_{1L}^{\perp q}(x, p_r^2) H_1^{\perp q}(z, z^2 k_T^2) \\ & \left. + 2(1-y) \frac{p_r \cdot S_r}{M} \frac{p_r^1 k_r^2 + p_r^2 k_r^1}{MM_h} h_{1T}^{\perp q}(x, k^2) H_1^{\perp q}(z, z^2 k_T^2) \right\}. \end{aligned} \quad (20)$$

Now let us consider the differential cross section for one quark flavour, σ_q , integrated with different weights depending on the final hadron transverse momenta and the direction of the nucleon transverse polarization with respect to virtual photon direction, $w_i(P_{h\perp}, \hat{S}_r)$:

$$I_i = \int d^2 P_{h\perp} w_i(P_{h\perp}, \hat{S}_r) \sigma_q. \quad (21)$$

(i) $w_1(P_{h\perp}, \hat{S}_r) = 1$.

Taking into account that $I_i = \int d^2 k_T d^2 p_T w_i(z(p_r - k_r), \hat{S}_r) \{ \dots \}$ and that odd powers of k_r^1, k_r^2 and p_r^1, p_r^2 give zero contribution to I_i , we find cross sections involving the transverse momentum-integrated distribution and fragmentation functions

$$I_1 = [1 + (1-y)^2] f_1(x) D_1(z) + \lambda_e \lambda y (2-y) g_1^q(x) D_1^q(z). \quad (22)$$

(ii) $w_2(P_{h\perp}, \hat{S}_r) = (-P_{h\perp} \cdot \hat{S}_r/z) = (|P_{h\perp}|/z) \cos(\phi_h^\ell - \phi_s^\ell) = (k_r - p_r) \cdot \hat{S}_r$.

The surviving terms upon integration are

$$I_2 = \lambda_e M |S_r| y (2-y) g_{1T}^{(1)q}(x) D_1^q(z) - M_h |S_r| 2(1-y) h_1^q(x) H_1^{\perp(1)q}(z) \sin 2\phi_s^\ell, \quad (23)$$

Note that the first term is proportional to the lepton polarization, while the second is not. One can also see that integrating over ϕ_s^ℓ (which is equivalent to integration over ϕ^ℓ) the second term $\propto \sin 2\phi_s^\ell$ in the above result vanishes and we get the result of our previous paper (Ref. [10]).

(iii) $w_3(P_{h\perp}, \hat{S}_r) = (P_{h\perp}^1 \hat{S}_r^2 + P_{h\perp}^2 \hat{S}_r^1)/z = (|P_{h\perp}|/z) \sin(\phi_s^\ell + \phi_h^\ell)$.

The surviving contributions are

$$I_3 = \lambda_e M |S_r| y (2-y) g_{1T}^{(1)q}(x) D_1^q(z) \sin 2\phi_s^\ell - M_h |S_r| 2(1-y) h_1^q(x) H_1^{\perp(1)q}(z). \quad (24)$$

As in the previous case the second term is independent of the lepton polarization and appears due to the Collins single spin asymmetry.

(iv) $w_4(P_{h\perp}, \hat{S}_r) = (P_{h\perp}^1 P_{h\perp}^2 / 2z^2) = (|P_{h\perp}|^2 / 4z^2) \sin 2\phi_h^\ell$.

The surviving contribution is

$$I_4 = MM_h \lambda 2(1-y) h_{1L}^{\perp(1)q}(x) H_1^{\perp(1)q}(z). \quad (25)$$

- (v) One can use another $w(P_{h\perp}, \hat{S}_T)$ to get separate contributions from $h_{1T}^q(x, p_T^2)$ and $h_{1T}^{\perp q}(x, p_T^2)$. For example $w_5(P_{h\perp}, \hat{S}_T) \propto P_{h\perp}^1 P_{h\perp}^2 (P_{h\perp} \cdot \hat{S}_T)$ will give another combination of $h_{1T}^q(x, p_T^2)$ and $h_{1T}^{\perp q}(x, p_T^2)$, containing higher (in transverse momentum space) moments of distribution and fragmentation functions. But to separate the contribution of $h_{1L}^{\perp q}(x, p_T^2)$ the weight factor w_4 suffices.

3. Approximations

In Ref. [10] we investigated $g_{1T}^{(1)q}$ by employing the relation with g_T (Eq. (14)) and the approximation of the latter by the Wandzura-Wilczek part determined by the polarized quark distribution function g_1^q . This led to

$$g_{1T}^{(1)q}(x) \simeq x \int_x^1 dy \frac{g_1^q(y)}{y}. \quad (26)$$

Here we want to follow a similar route and use the relation between $h_{1L}^{\perp(1)q}$ and h_L^q (Eq. (15)) and the separation of the latter in interaction-independent and interaction-dependent parts [2],

$$h_L^q(x) = \frac{2}{x} h_{1L}^{\perp(1)q} + \frac{m}{Mx} g_1^q + \tilde{h}_L^q. \quad (27)$$

Omitting the interaction-dependent term \tilde{h}_L^q and the quark mass term and using Eq. (15) one gets the differential equation

$$2 \frac{d}{dx} h_{1L}^{\perp(1)q}(x) - \frac{h_{1L}^{\perp(1)q}(x)}{x} = h_1^q(x), \quad (28)$$

leading with the requirement $h_{1L}^{\perp(1)q}(1) = 0$ to

$$h_{1L}^{\perp(1)q}(x) \simeq -\frac{1}{2} x \int_x^1 dy \frac{h_1^q(y)}{y}. \quad (29)$$

Next one can use for an order of magnitude estimate $h_1^q(x) \simeq g_1(x)$, which is valid for example in the bag model [7]. Thus, in this approximation

$$h_{1L}^{\perp(1)q}(x) \simeq -\frac{1}{2} x \int_x^1 dy \frac{g_1^q(y)}{y}. \quad (30)$$

We will use for numerical estimation the values obtained using parametrization of DF's from Ref. [11].

Next, let us turn to the estimate of $H_1^{\perp(1)q}(z)$. Collins [6] suggested the following parametrization for the analyzing power in transversely polarized quark fragmentation

$$A_C(z, k_T) \equiv \frac{|k_T| H_1^{\perp q}(z, z^2 k_T^2)}{M_h D_1^q(z, z^2 k_T^2)} = \frac{M_C |k_T|}{M_C^2 + |k_T^2|}, \quad (31)$$

where $M_C \simeq 0.3\text{--}1.0$ GeV is a typical hadronic mass. This parametrization exhibits the kinematic zero when $k_T = 0$, the leading twist asymmetry when $k_T = \mathcal{O}(M)$, and the higher twist asymmetry when $k_T \gg M$. Now, assuming a Gaussian parametrization for the unpolarized fragmentation function

$$D_1^q(z, z^2 k_T^2) = D_1^q(z) \frac{R^2}{\pi z^2} \exp(-R^2 k_T^2), \quad (32)$$

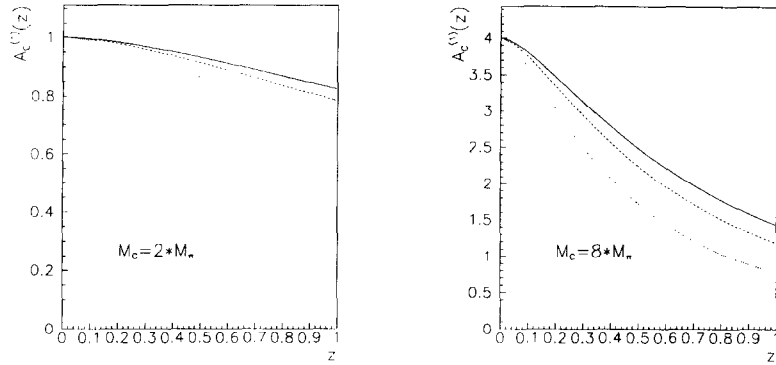


Fig. 1. $H_1^{\perp(1)u}(z)/D_1^u(z)$ for different values of M_C ; solid line – $\langle P_{h\perp}^2 \rangle = 0.98 \text{ (GeV/c)}^2$, dashed line – $\langle P_{h\perp}^2 \rangle = 0.70 \text{ (GeV/c)}^2$ and dotted line – $\langle P_{h\perp}^2 \rangle = 0.36 \text{ (GeV/c)}^2$.

one obtain

$$H_1^{\perp(1)q}(z) = D_1^q(z) \frac{M_C}{2M_h} \left(1 - M_C^2 R^2 \int_0^\infty dx \frac{\exp(-x)}{x + M_C^2 R^2} \right). \quad (33)$$

Note, that $R^2 = z^2/\langle P_{h\perp}^2 \rangle$ where $\langle P_{h\perp}^2 \rangle$ is a hadron mean-square momentum in the quark fragmentation. According to different analyses [12] $\langle P_{h\perp}^2 \rangle \simeq 0.36\text{--}0.98 \text{ (GeV/c)}^2$. Fig. 1 represents the ratio $A_C^{(1)}(z) \equiv H_1^{\perp(1)u}(z)/D_1^u(z)$ for different values of $\langle P_{h\perp}^2 \rangle$ and M_C .

4. Numerical results

We will consider production of π^+ -mesons on the proton target. In order to get an order of magnitude estimate we note that the cross section is given predominantly by scattering on the u -quark. Consider the target longitudinal spin asymmetry defined as

$$A(x, y, z; \lambda) \equiv \frac{\int d\phi^l \int d^2 P_{h\perp} \frac{|P_{h\perp}^2|}{4z^2 M_h^2} \sin 2\phi_h^\ell (d\sigma^+ - d\sigma^-)}{\int d\phi^l \int d^2 P_{h\perp} (d\sigma^+ + d\sigma^-)}, \quad (34)$$

where $+$ ($-$) denotes target positive (negative) longitudinal polarization. Using I_1 and I_4 we see that for both polarized and unpolarized lepton this asymmetry is given by

$$A(x, y, z; \lambda) = -\lambda \frac{2(1-y)}{1+(1-y)^2} \frac{h_{1L}^{\perp(1)u}(x) H_1^{\perp(1)u}(z)}{f_1^u(x) D_1^u(z)}. \quad (35)$$

Note, that this expression is valid for unpolarized as well as for polarized lepton beam.

For polarized leptons one can consider also the asymmetry defined as

$$A_1(x, y, z) \equiv \frac{\int d\phi^l \int d^2 P_{h\perp} \frac{|P_{h\perp}^2|}{4z^2 M_h^2} \sin 2\phi_h^\ell (d\sigma^{++} - d\sigma^{+-})}{\int d\phi^l \int d^2 P_{h\perp} (d\sigma^{++} - d\sigma^{+-})}, \quad (36)$$

where the first (second) superscript of $d\sigma$ denotes lepton (target) polarization, leading to

$$A_1(x, y, z) = \frac{2(1-y)}{y(2-y)} \frac{h_{1L}^{\perp(1)u}(x) H_1^{\perp(1)u}(z)}{g_1^u(x) D_1^u(z)}. \quad (37)$$

With the approximation for $h_{1L}^{\perp(1)u}$ and using the ratio $x \int_x^1 dy \frac{g_1^u(y)}{f_1^u(x)} / f_1^u(x)$ as calculated in [10] (see Fig. 3 there), which reaches a maximal value of 0.08 at $x \simeq 0.5$, we obtain for small y -values and moderate z -values $A(x \simeq 0.5, y \simeq 0.1, z \simeq 0.3; \lambda) \simeq (0.04-0.12) \lambda$.

The asymmetry A_1 is related to A ,

$$A_1(x, y, z) = \frac{1 + (1-y)^2}{\lambda y(2-y)} \frac{f_1^u(x)}{g_1^u(x)} A(x, y, z; \lambda). \quad (38)$$

The ratio $g_1^u(x)/f_1^u(x)$ is presented in Fig. 1 of Ref. [10] and leads to $A_1(x \simeq 0.2-0.5, y \simeq 0.1, z \simeq 0.3) \simeq 0.4-2.8$.

Finally, let us consider the following weighted target transverse-spin asymmetry:

$$A_T(x, y, z; |S_T|) \equiv \frac{\int d\phi^\uparrow \int d^2 P_{h\perp} \frac{|P_{h\perp}|}{zM_h} \sin(\phi_s^\uparrow + \phi_h^\uparrow) (d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi^\uparrow \int d^2 P_{h\perp} (d\sigma^\uparrow + d\sigma^\downarrow)}, \quad (39)$$

where $\uparrow (\downarrow)$ denotes target up (down) transverse polarization. Using I_1 and I_3 we see that for both polarized and unpolarized lepton this asymmetry is given by

$$A_T(x, y, z, |S_T|) = -|S_T| \frac{2(1-y)}{1 + (1-y)^2} \frac{h_1^u(x) H_1^{\perp(1)u}(z)}{f_1^u(x) D_1^u(z)}. \quad (40)$$

With the approximation $h_1^u(x) \simeq g_1^u(x)$ and using the ratio $g_1^u(x)/f_1^u(x)$ from Ref. [10] we see that asymmetry $A_T(x \simeq 0.2-0.5, y \simeq 0.1, z \simeq 0.3; |S_T|) \simeq -(0.4-2.1)|S_T|$. Thus, one sees that the A_T asymmetry is an order of magnitude larger than A . Remember that both asymmetries arise due to the Collins effect in transversely polarized quark fragmentation but in the second case this quark polarization is coming from the intrinsic transverse momentum.

In Ref. [6] an estimate for $H_1^{\perp q}/D_1^q$ has been given. In Ref. [2] a full analysis of lepton-hadron scattering was presented, including transverse momentum dependence in distribution and fragmentation functions. The k_T -moments of these functions are related to twist-3 functions. For the latter we consider only the 'interaction-independent' part, which involves twist-2 functions. For the latter we finally assume that the helicity and transverse spin distributions are identical. This allows us to crudely estimate azimuthal asymmetries expected in a number of observables. The transverse polarization of a quark in a longitudinally polarized nucleon arises due to intrinsic transverse momentum effects and is proportional to $p_T h_{1L}^{\perp q}$, which vanishes at $p_T = 0$, whereas in the transversely polarized nucleon it can be nonzero at $p_T = 0$. This is the reason that the polarization azimuthal asymmetry for transversely polarized nucleons (A_T) is much larger than for longitudinally polarized nucleons (A).

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